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Water quality responses to fire, with particular reference to organic-rich wetlands and the Swan Coastal Plain: a review

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Abstract

The unconfined aquifers on the Swan Coastal Plain provide the population of Perth with much of its scheme water and the questionable effects of fire on the quality of surface and ground water, and recharge volumes, remain unanswered. In addition, recent concerns about fire in organic sediments and the effects of groundwater decline on acid sulphate soils have increased the need for research. Based mainly on a review of relevant literature, we formulate hypotheses as to the possible effects of fire on water quality in wetlands, particularly organic-rich ones, on the Swan Coastal Plain. Water quality responses may occur due to catchment effects (increased runoff and erosion, explainable by removal of canopy cover and changes in soil water repellency, resulting in nutrient and sediment fluxes into the wetland, elevated cation concentration and a shift to alkalinity) and atmospheric effects (the return to the ground of dissolved volatilized reactive and particulate compounds). For both these effects, on the Swan Coastal Plain the over-riding catchment influences are the ways in which the wetlands interact with the shallow unconfined aquifers and how a fire and a changed fire regime might affect this relationship. Profound changes to water quality are possible upon rehydration of burnt or overheated (organic) soils. Cracking and erosion caused by fire can expose acid sulphate soils to oxidizing conditions, resulting in lower pH and mobilization of heavy metals. Superimposed on all these changes are the trophic consequences and how they might influence water quality. Finally we discuss the secondary effects that arise from management attempts to control or prevent fire in a wetland, such as fire suppression effects, flooding or trenching to stop a peat burn, or prescription burning around a wetland to reduce fuel loadings, each of which might trigger or exacerbate any of the above mentioned water quality responses. Management should therefore apply a precautionary approach to prevent irreversible losses (like erosion of organic soil profiles) and otherwise use an adaptive management approach to test the hypotheses stated herein.

Keywords: fire, water quality, organic-rich wetlands, Swan Coastal Plain, acidification

Introduction

Assessments of the impact of fire rarely examine consequences for water quality, and by extension aquatic biodiversity. This is probably because wetlands are perceived to be beyond the influence of fire. On the Swan Coastal Plain in Western Australia there are several reasons why this shortfall of knowledge needs to be addressed. The unconfined aquifers on the Plains provide the population of Perth with much of its domestic, industrial and commercial water and the questionable effects of fire on the quality of surface and ground water, and recharge volumes remain unanswered. In addition, fire in organic sediments is a growing concern (Horwitz *et al.* 1999; Horwitz *et al.* 2003), as are the effects of groundwater decline on acid sulphate soils (Sommer & Horwitz 2001; Appleyard *et al.* 2004).

The Swan Coastal Plain (SCP) can be characterized as a bioregionally heterogeneous wetland system composed of permanent and ephemeral shallow lakes in depressions as well as sumplands, damplands and palusplains, dissected by occasional creeks and rivers discharging into estuarine lagoons (Semeniuk 1987). On the plains wetlands are related to the ridges and interdunal depressions of the three dune systems that run north-south, and parallel with the coastline, over the western two-thirds of the Swan Coastal Plain (Seddon 1972). The unconsolidated Quaternary deposits on the SCP form a regionally extensive unconfined aquifer known as the 'superficial aquifer'. There are two major groundwater flow systems in the Perth region known as the Gnangara Mound and Jandakot Mound (flow systems) (Davidson 1995). Although some of the wetlands are perched, the majority interact with the groundwater table in some way.

Water quality in the wetlands is a reflection of the particular geomorphic unit on which they are situated. Thus wetlands on the Quindalup and Spearwood Dunes tend to be well buffered, with neutral to relatively high pH (a reflection of the underlying calcareous and limestone sediments), while wetlands on the strongly leached Bassendean dunes are generally coloured, poorly buffered and acidic (Water Authority of Western Australia 1995). By extension, the water quality response to any disturbance, including fire, will also be strongly dictated by their geomorphic settings. Another important factor influencing water quality response is the amount of organic matter in the aquatic sediments. The wetlands under discussion have varying amounts of organic matter, ranging from very low levels to true peat sediments with the proportion of organic matter content, in some cases, in excess of 80 % (Teakle & Southern 1937).

Most of the wetlands are surrounded by at least a minimal buffer of either bushland (with those in better condition often as declared State nature reserves), or parkland gardens managed by local government authorities. By virtue of their urban or semi-rural settings, the wetlands are invariably, and regularly exposed to accidentally or maliciously lit fires. Often the fires are restricted to surrounding bushland or littoral vegetation as their progress deeper into the wetland is impeded by the presence of water.

In recent years, however, over-extraction of groundwater, exacerbated by declining rainfall, has lowered groundwater tables (in some instances markedly), and consequently wetland water levels (Water & Rivers Commission 2001). Some wetland systems, for example those on the northern and eastern Gnangara Mound (the Lexia suite of wetlands, Bombing Range wetlands, wetlands of the Yeal Nature Reserve, linear chain of wetlands between Yanchep and Lake Goolellal, and those in the Mariginiup -Gnangara suite) have in the recent past become so dry in summer that nearby fires have passed through the wetland areas, either severely cracking the organic soils or actually burning them (Fig. 1). The passage of fire into a wetland may be enhanced by the presence of introduced plants, particularly grasses (Davis & Froend 1999) and sedges.

Whether wetland organic profiles are cracked or burnt, or whether only wetland vegetation, or only the surrounding catchment is burnt, water quality will be at least temporarily affected. But how, and how will water quality changes affect the ecological values of such wetlands? The aim of this paper is to examine the literature and describe the water quality responses to fires that occur in or around wetlands, and to formulate hypotheses that state their relevance for wetlands on the SCP and other similar ecosystems.

Methods

Literature searches were conducted via knowledge bases, principally the Australian Agriculture and Natural Resources Online (AANRO)(incorporating databases of Streamline, ARRIP and ABOA) at Land and Water Australia; the Cooperative Research Centre for Hydrology's Bushfire Hydrology website; Google and Google Scholar (www.google.com and www.scholar.google.com) and the AGRICOLA database at the Water Quality Information Centre at the National Agricultural Library, Agricultural Research Service, United States Department of Agriculture. Searches were performed using the following primary keywords: fire, water quality, organic soil (or peat), in combination with the following secondary keywords: soil repellency, hydrology, nutrients, trophic response, heavy metals, acidification, review, and relevant biogeographic localities (like the Swan Coastal Plain, The Everglades, Sumatra etc.).

Figure 1. Impact of a wildfire which took place in the Bombing Range wetlands in 1995–1996. The organic sediments are cracked and exposed, showing bleached diatomaceous earth. Elsewhere sedge-pedestals and meter-deep cracked profiles were visible (not shown on photo).Cracks shown here are up to 5cm wide. Photograph B. Sommer 1997.

Although the general fire literature is extensive, comparatively little has been published on the effects of fires on water quality *per se*, and most material that does exist deals with either catchment effects (flowing water systems, for instance Townsend & Douglas 2000), in hilly or mountainous forested areas (see for example Chessman 1986; Bayley *et al.* 1992; Earl & Blinn 2000; Shakesby *et al.* 2003), or the fate of nutrients associated with burns in productive forests (see Ranalli 2004). Drawing on the identified literature sources, the general fire literature, the discussion of fire and water quality in Horwitz *et al.* (2003) and on our own experiences on the SCP, this paper discusses the potential consequences of fire on water quality in terms of:

a) catchment effects;

b) atmospheric effects;

c) rehydration of burnt or overheated (organic) soils;

d) trophic consequences; and

e) fire suppression and fire prevention effects.

In discussing these five themes, we have highlighted, where appropriate, their relevance to wetlands on the SCP.

Potential changes to water quality following a fire

Catchment effects

The potential impact of fire on wetland water quality will depend on the fire regime (the extent, frequency, intensity, season and duration of the fire), the size of the catchment affected by fire, the slope/topography of the terrain, climatic conditions, the type of vegetation, as well as moisture content and depth of any organic-rich soil (see Humphreys & Craig 1981; Ranalli 2004; Rhodes & Davis 1995). The larger and steeper the catchment, the more vulnerable the water body will be to the surrounding terrestrial environment (Rhodes & Davis 1995). The dissolvable and erodible residue of a fire will generally find its way into a wetland, changing water quality. Vegetation ash derived from the surrounding catchment is typically alkaline and rich in extractable Mg, Ca and K (Gimeno Garcia *et al.* 2000). Because of this, the pH of receiving water bodies tends to increase following a catchment fire (Ranalli 2004). Palaeolimnological records from northern hemisphere lakes show that diatom-inferred pH rises abruptly at sedimentary horizons containing evidence of fire (i.e. charcoal) (Korhola *et al.* 1996; Rhodes & Davis 1995).

It is also well known that, depending on the intensity, fire releases varying types and quantities of soil nutrients (Belillas & Rodà 1993; Christensen 1994; DeBano *et al.* 1998; McNabb & Cromack 1990). Some of these, in particular phosphorus, will be washed, blown, or diffused into wetlands from ash. For nitrogen Ranalli (2004 p.20) concluded from his review of the literature that:

> ...the major source of ammonium to surface water during and immediately following a fire is from the dissolution of ammonium volatilized from the combustion of organic matter into precipitation or into a stream or lake. The major source of nitrate immediately following a fire is the nitrification of ammonium released from the combustion of organic matter.

Catchment hydrology effects are well described in the literature: increased water yield following fire is the norm. This results from the destruction of vegetation and litter cover, and reduced infiltration resulting from the development of water-repellency of catchment soils (Debano 2000; Emmerich & Cox 1994; Letey 2001; Rambal 1994; Scott & van Wyk 1992; Shakesby *et al.* 2003). Debano (2000) summarizes the process leading to repellency, where heat is produced by combustion of the litter layer on the soil surface, vaporizing organic hydrophobic substances, which are then moved downward in the soil along the steep temperature gradients until they reach the cooler underlying soil layers, where they condense, coating and chemically bonding to mineral soil particles. These are general effects, and exceptions do occur; Shakesby *et al.* (2003) describe a fire of sufficient heat to patchily destroy pre-fire surface repellency, rather than generate post-fire repellency. Nevertheless, the volume of water entering a wetland may be temporarily increased following a fire.

The increased water yields and surface flows over exposed soils result in increased catchment erosion (Belillas & Rodà 1993; Emmerich & Cox 1994; Menaut *et al.*1992; Wilson 1999). This in turn leads to increased turbidity in receiving water bodies. Townsend & Douglas (2000) demonstrate that the degree of erosion and amount of suspended sediment is a function of the intensity and season of the fire. Reducing the intensity of the fires allows catchment vegetation to recover, decreasing the erosive effects of raindrops and overland flow (Townsend *et al.* 2004).

On the SCP, runoff-related effects resulting from fire in a catchment might be relatively minimal and highly localized due to the low relief in the bioregion, and the small nature of surface catchments in non-urbanized parts of the Plain. Local erosional events may occur, particularly for sandy soils that are non-wetting (and hence seasonally water repellent) and exposed to infrequent heavy rainfall events in summer, depositing coarse sediment and some dissolved ions into littoral habitats of wetlands. The nature of the sediment suggests that such events are unlikely to cause significant changes in turbidity. Similarly, the alkaline ash produced from a fire in the catchment is unlikely to be washed into surface waters except from riparian areas and under the extreme rainfall circumstances described above. For groundwater dependent wetlands on the SCP the more crucial catchment-related fire issue is whether fire exacerbates the naturally water repellent sandy sediments, delaying seasonal changes to infiltration rates, and ultimately reducing groundwater recharge, and what the effect of fire intensity will be on this relationship.

Atmospheric considerations

Biomass burning releases large quantities of reactive compounds to the atmosphere, in particular NOx, hydrocarbons, CO_2 and sulphur compounds (Anderson 1996; Fishman *et al.* 1993). Large quantities of soot and organic carbon are also emitted. From here they can fall to the ground in the form of dust, or become hydrated and return to the ground in a dissolved form with precipitation. When they fall into poorly buffered waterbodies, nitrogen and sulphur compounds dissolved in 'acid rain' may oxidize and cause acidification (Roser 1997).

Fire in organic soils is extremely difficult to extinguish. Smoke generated from peat soils is chemically different from most other types of smoke and more smoke per hectare is created than that of vegetation fires on other soil types (see Hinwood & Rodriguez 2005, this issue). Partial (restricted) combustion releases to the atmosphere a variety of chemical compounds, which not only have the potential to affect wetland water quality, but are also deleterious to human health (Fishman *et al.* 1993).

It is doubtful whether these issues are significant influences on wetland water quality on the SCP because the most probable time of the year when this rehydration would result in acidic precipitation is that season (winter) when catchment or wetland fires are least likely to occur, and when smoke would be carried eastwards by the strong prevailing westerlies. However, the water quality implications for smoke generated from wood heaters in winter, or smoke haze over the SCP from autumn prescribed burns in the lower south-west of the State requires investigation.

Rehydration of burnt or overheated (organic) soils

One of the most obvious disadvantages of fire is that it has the capacity to consume considerable amounts of accumulated organic matter. The edges of organic-rich wetlands are most vulnerable because the water level is less of an influence, the organic soils are shallow and dry out more easily and their loss exposes mineral soils more readily. The loss of organic matter from wetlands can have a number of contrasting consequences for water quality. Since much of the acidity of peat bogs is due to organic acids (Wetzel 2001), combustion of organic soils should result in an increase in alkalinity, and this in combination with the ash effects described above, should result in a rise of pH in these systems.

It would be incorrect to believe that fire invariably increases the pH of water bodies. Peat can contain large amounts of organic sulphur, not all of which is volatilized in a fire. The portion of sulphur not removed by fire could eventually become available for oxidation and the production of sulphuric acid. The peat sediments also, more often than not, contain reduced inorganic sulphur (*e.g.* metal sulphides such as pyrite [FeS_2]), rendering them 'Acid Sulphate Soils'. Peat on the SCP can contain up to 15 % by weight of oxidizable sulphur (Appleyard *et al.* 2004). Acid Sulphate Soils are abundant in coastal regions around Australia, including the SCP (National Working Party on Acid Sulphate Soils 2000). They largely originate from sulphate in seawater which inundated land as sealevels rose some 10,000 years ago, subsequently mixing with land sediments containing iron oxides and organic matter (National Working Party on Acid Sulphate Soils 2000). They are relatively stable under anaerobic conditions, but when exposed to air the sulphides oxidize. When subsequently wetted they react with water to produce sulphuric acid. The capacity for organic rich wetlands in south-western Australia to undergo an acidic response upon aeration through drainage has long been recognised (see Teakle & Southern 1937), and more recently through drought and groundwater decline (Sommer & Horwitz 2001).

Complex relationships may exist between drying due to drought or other causes, and resulting acidification, and the loss of organic profiles due to subsequent fires and further water quality consequences, as evidenced by a lake in south-coastal Western Australia described by Horwitz *et al.* (1999). They found the lake water to be clear and acidic (pH 3.2 – 3.7) with extremely high redox values (360– 460 mV) before the October 1994 fire. When visited after the fire in July 1996 they noted that the dry surface of the lake was dominated by iron precipitate. They suggested that their observations imply at least two acidification events, one before and one after the fire. Drying prior to 1994 would have produced the cracks in the soil causing the oxidation of soil deeper in the profile, while the fire may have subsequently exposed passive acid sulphate layers. It was noted in Horwitz *et al.* (2003) that the inputs of alkaline ash from the burnt catchment were apparently insufficient to neutralize the sulphuric acid that formed after reinundation of the lake.

Several organic-rich wetlands on the eastern Gnangara Mound (Lexia wetlands, Melaleuca Park EPP wetland) have revealed pH values lower than 4 during routine monitoring visits (see for instance Clark & Horwitz 2004). It is not unreasonable to speculate that such low pH values could be exacerbated by fire (either burning the soil, or overheating it to produce cracks), given the relatively frequent occurrence of fire in the area. These wetlands occur on the poorly buffered Bassendean sands. Where such acidification events are possible, it can also be hypothesized that cracked soils upon rehydration will allow acidified water to enter the groundwater system, forming an acidic plume. Elsewhere on the SCP where sediments are buffered, the immediacy of the acidic response resulting from drought or fire may be delayed, or the buffering gradually eroded, as appears to be the case at Lake Mariginiup where the spring pH of surface waters has very gradually been decreasing each year over the last 4 years (Clark & Horwitz 2004) and a fire in the lake actually burnt sediment in 2002 (Fig. 2).

There are anecdotal records of horticulturalists on the SCP burning wetlands to produce an immediate alkaline response to temporarily over-ride the acidity of the soils and result in a pulse in vegetative productivity (S. Appleyard, pers. comm.), but at the same time gradually exposing more and more of the anaerobic sediments to oxidation. Such regular burning is said to be the cause of a fire at Coogee Springs in 2002 where massive soil loss occurred due to soils being unseasonally dry from local drawdown of the water table (Horwitz unpubl. data). The wetland has not refilled since and no measurements have been made of groundwater quality underneath the wetland.

Whether the pH of surface waters increases or decreases as a consequence of fire has important repercussions for other chemical characteristics of the water. If acidification occurs, minerals in soils dissolve and liberate soluble and colloidal aluminium and iron (Fitzpatrick 2003) and other metals and metalloids; under these conditions the iron and aluminum can coagulate with particulate matter and settle out, leaving the water column clear. Likewise, in extreme acidification events,

Figure 2. Burnt organic soils in Lake Mariginiup, Swan Coastal Plain, showing a circular depression up to 5 m wide where soil has been consumed to a depth of over 30 cm, exposing the roots of a *Melaleuca* sp. which has been killed in the process. Photograph J.M. Benier, 2003.

organic humic substances responsible for colour will precipitate with dissolved metals and phosphates, leaving the water colourless and low in phosphorus (see for instance Sommer & Horwitz 2001).

Of major concern in sulphidic sediments is the potential for heavy metals to be mobilized following oxidation, thereby contaminating surface waters. On the SCP, arsenic and aluminium in affected groundwaters have reached extremely high levels (Appleyard *et al.* 2004; Hinwood *et al.* 2005).

Trophic effects

For all aquatic habitats in well-vegetated catchments, it can be hypothesized that removal by fire of the shade and organic matter provided by riparian cover, and the removal of catchment leaf litter, may temporarily at least reduce organic matter input. Fire will expose those systems to more sunlight, elevated temperatures and greater levels of water column and overall wetland photosynthesis. The broader question has, therefore, focused traditionally upon the impact of changing fire regimes on the trophic dynamics in wetlands as they temporarily shift from heterotrophy to autotrophy.

From the catchment effects described earlier, increased nutrient concentrations, especially in conjunction with elevated pH, and increased light due to the removal of canopy by fire, leads to a rapid increase in productivity, usually by opportunistic algal species, with a potential for nuisance algal blooms. In some instances the inflow of nutrients and base cations might be beneficial to specific aquatic systems. Increased suspended sediments and turbidity can have a variety of impacts on aquatic organisms, including alteration of the light regime to which the biota has become adapted, smothering of aquatic plants and animals, and reducing the availability of oxygen.

In an acidification scenario, the combined effects of low pH (and associated metal toxicity), low nutrients and greater exposure to UV radiation can have an impact on aquatic communities. As well as being toxic for humans if ingested, high concentrations of these metals will have significant trophic effects in wetlands. For instance inorganic soluble ionic aluminium is toxic to fish, amphibians, macroinvertebrates, zooplankton, phytoplankton and algae, although a "toxic level" has not been defined (Schindler, 1988; Herrman, 2001). It is, however, difficult to differentiate between the effects of ionic Al and low pH (Herrman, 2001); in combination they cause species reductions. Sommer & Horwitz (2001) noted significant changes in aquatic macroinvertebrate assemblages in a wetland on the Gnangara groundwater mound on the SCP (Lake Jandabup) affected by acidification. While the acidification was due, in this case, to drought and lowered water tables over a period of approximately 5 years, the net result may be similar to that of fire. There were 'local' extinctions of highly sensitive taxa such as amphipods (*Austrochiltonia*), mayflies (Caenidae) and planorbid gastropods; decreases in abundance of sensitive taxa such as ostracods and isopods (Amphisopidae); and increases in abundance of apparently acid-tolerant taxa (macrothricid cladocerans and the larvae of the sandfly Ceratopogonidae). Biogeochemical cycles in acidified waterbodies become disrupted as the microbial community is also affected by low pH. Whereas the effects of increased alkalinity and nutrient levels tend to be short-lived (see for instance Earl & Blinn 2000), recovery from acidification can be relatively slow, particularly if much organic matter were lost from the wetland. Organic matter is required to reinstate reducing conditions and increase alkalinity by providing a substrate for microbes.

The effects of fire management on water quality

Water quality in wetland systems will respond to attempts to extinguish, or suppress, fire in the wetland or its catchment, as well as attempts to prevent fire from spreading into a wetland.

Fire suppression commonly uses retardant chemicals and fire suppressant foams. Hamilton *et al.* (1996) found that both fire-retardant and foam-suppressant chemicals were very toxic to aquatic organisms including algae, aquatic invertebrates and fish (see also Buhl & Hamilton 2000). They suggested that fire-control managers need to consider protection of aquatic resources from toxic effects, especially if endangered species are present.

Another technique considered for extinguishing fires in organic soils is flooding with water extracted or

Table 1

Summary of the effects of fire on water quality, showing four categories of effects, and the general consequences for water quality, their duration of change, and the trophic consequences, all derived from relevant literature. The last column summarises the hypothetical implications of this review for the situation on the Swan Coastal Plain.

Broad fire effects	Water quality responses	Duration of change	Trophic consequences	Implications for Swan Coastal Plain
Catchment effects (runoff, deposition)	Elevated base cations	Short term	Increased productivity	Highly localized only
	Alkalinity	Short term	Increased productivity	Highly localized only
	Elevated nutrient concentration	Short term	Increased productivity	Probable occurrence but magnitude of nutrient shift dependent on many factors
	Sediment input	Short and long term	Smothering, increased turbidity	Local smothering in littoral zone possible; turbidity change unlikely
	Groundwater recharge	Short term	Possible change to wetland surface water regime	Possible seasonal delay to recharge depending on intensity of burn and repellency of soil
Atmospheric effects of a fire in a catchment	Return to the ground of dissolved volatilized reactive and particulate compounds	Short term	Acidify wetland (change structure of aquatic communities)	Unlikely due to seasonal influences unless fires are followed by (intense) rain
Rehydration of burnt or overheated (organic) soils	Alkalinity	Short term	Increased productivity	Highly localized only
	Acidification -Lower pH -Water clarity -Loss of colour -Heavy metals	Medium term to long term	Decreased in water productivity, altered structure of aquatic communities (loss of sensitive species, predominance of acid-tolerant forms).	Localized, potential for groundwater plume
Fire suppression effects	Toxic chemicals	Depends on half life of chemicals	Altered structure of communities, local extinctions	Probable assuming that response of local flora and fauna is equivalent to other taxa tested elsewhere
	Water movement	Long term	Introductions and potential extinctions	Information on sources of water insufficient to discuss implications
	Acidification from drainage/trenching /flooding	Medium term to long term	(see above)	(as above)
Fire Prevention Effects	(similar to catchment and atmospheric effects as above)	(as above)		

diverted from a nearby source. It is commonly reasoned that the potential for translocation of unwanted aquatic species, the accidental removal of endangered species (Jimenez & Burton 2001) or deleterious water quality changes, when water is moved via water carrying devices for fire suppression, are outweighed by the potential damage to wetlands from burning. As far as we can tell this reasoning has never been critically examined, and reliable data are required from south-western Australia to assess its validity.

As well as flooding, trenching has been applied to attempt to arrest the progress of burning peat in organic-rich soils in south-western Australia. When the flooding or drenching involves any digging of organic soils, or construction of trenches, the possibility is raised of exposing acid sulphate soils to aeration and developing a localized acidification event.

Where wetlands have significant ecological or cultural value, their protection using fire prevention methods involves the reasoning that reducing the biomass at the margins of a wetland will lessen the risk that a wildfire or an escaped burn will be able to be carried into that wetland. Whether this reasoning is sound or not, such prescription burns around wetlands will have at least the catchment, atmospheric and trophic implications for water quality as discussed in this paper.

General Discussion

Table 1 summarises the issues presented in this paper, and the implications of the findings for the organic- rich wetlands on the SCP. While the literature examined has been useful for framing categories of water quality response as above, we note that there have been no studies into the effects of fire on wetlands on the SCP in general, *let alone* the effects of fire on wetland water quality for this bioregion. Indeed fire, or a change in fire regime, are not mentioned by Davis & Froend (1999) in the context of disturbances to wetlands, and fire as a process is only briefly mentioned in Balla's (1994) otherwise comprehensive treatise on management issues for wetlands on the SCP.

The literature shows that fire regime in catchments certainly has implications for water quality. The question of the effects of fire intensity and seasonality on soil water repellency and thereby for recharge into unconfined aquifers, and runoff into wetlands, emerges as a critical one for managers of the city of Perth's water resources and wetlands on the Plain.

A conundrum was raised by Horwitz *et al.* (2003): why are organic soils burning more often in recent times when they should be persistently damp even during dry seasons or drought, and thereby able to resist the passage of a fire? This suggests either a fire regime change, or organic soils are drying out more than previously, or both. Declining rainfall and anthropogenic effects such as groundwater abstraction for domestic and horticultural purposes are undoubtedly rendering organic soils on the SCP drier than they have been for significant period of time (perhaps even thousands of years). Such drying results in a vulnerability to fire, particularly if more intense fires occur in what have become seasonally inappropriate times (any time from the period late spring to late autumn). The simultaneous occurrence of drought and fire is likely to increase on the SCP, as it is elsewhere (Hogenbirk & Wein 1991). A likely prognosis will be for fires to occur in organic soils until they resume their seasonal and yearly moisture levels, and/or until fire regimes, including arson attacks during hot periods, change.

The potential consequences for water quality of fire suppression and fire prevention demonstrate that fire management cannot rely on single approaches or quick fix solutions for fire in wetlands. Management should therefore apply a precautionary approach to prevent irreversible losses (like erosion of organic soil profiles) and otherwise use an adaptive management framework that will include testing the hypotheses stated herein.

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